Smart and Sustainable Manufacturing Systems

Salil Bapat,[1] Michael P. Sealy,[1] Kamlakar P. Rajurkar,[2] Tom Houle,[3] Kimberly Sablon,[4] and Ajay P. Malshe[5]

DOI: 10.1520/SSMS20210022

Applications of Hybrid Manufacturing during COVID-19 Pandemic: Pathway to Convergent Manufacturing

VOL. 6 / NO. 1 / 2022

doi:10.1520/SSMS20210022 / Vol. 6 / No. 1 / 2022 / available online at www.astm.org

TECHNICAL NOTE

Salil Bapat,[1] Michael P. Sealy,[1] Kamlakar P. Rajurkar,[2] Tom Houle,[3] Kimberly Sablon,[4] and Ajay P. Malshe[5]

Applications of Hybrid Manufacturing during COVID-19 Pandemic: Pathway to Convergent Manufacturing

Reference

S. Bapat, M. P. Sealy, K. P. Rajurkar, T. Houle, K. Sablon, and A. P. Malshe, "Applications of Hybrid Manufacturing during COVID-19 Pandemic: Pathway to Convergent Manufacturing," *Smart and Sustainable Manufacturing Systems* 6, no. 1 (2022): 12–22. https://doi.org/10.1520/SSMS20210022

Manuscript received May 14, 2021; accepted for publication November 2, 2021; published online January 12, 2022. Issue published January 12, 2022.

[1] School of Mechanical Engineering, Purdue University, 585 Purdue Mall, West Lafayette, IN 47907, USA, https://orcid.org/0000-0001-9694-2585 (S.B.)

[2] Mechanical and Materials Engineering Department, University of Nebraska-Lincoln, 820 N. 16th St., Lincoln, NE 68588, USA

[3] Matsuura Machinery USA, 325 Randolph Ave., Suite 100, St. Paul, MN 55102, USA

[4] Army Futures Command, 210 W. 7th St., Austin, TX 78701, USA

[5] School of Mechanical Engineering, Purdue University, 585 Purdue Mall, West Lafayette, IN 47907, USA (Corresponding author), e-mail: amalshe@purdue.edu

ABSTRACT

This paper presents the advancements in manufacturing science and the engineering learned because of the global emergencies resulting from pandemics. Established manufacturing processes strained to the limit delivering parts and services during the pandemic in industrialized as well as industrializing nations. These limitations call for manufacturing by integrating or hybridizing multiple processes and sometimes materials. This paper illustrates value propositions resulting from hybrid manufacturing by using pertinent case studies of a ventilator filter housing and an injection molding tool. This paper concludes by making a case for convergence of heterogenous materials, processes, and systems in a unified platform allowing adaptability, agility, and flexibility in manufacturing geared toward offering resilience in similar future global catastrophes.

Keywords

hybrid manufacturing, resilience, convergence

Introduction: COVID-19 Pandemic and Manufacturing Lessons Learned

IMPACT OF COVID-19 PANDEMIC

The coronavirus disease (COVID-19) pandemic globally impacted day-to-day operations in an unprecedented manner. The situation resulted in a demand for virtual operations as well as remote interactions along with the enhanced use of "digital" technologies across

TABLE 1
Impact of COVID-19 and lessons learned

Observations	Lesson Learned
The physical technology most crucial for curbing the COVID-19 spread is a mask.[12]	Effectiveness of a solution is not tied to design complexity but to the function it provides with simplicity.
Heightened demand for personal protective equipment (PPE) along with masks resulted in them being manufactured by several industries that do not traditionally cater to them.[13–15]	Adaptability of existing infrastructure is important. Rapid retooling and turnaround is needed to aid reconfigurability by repurposing existing equipment and knowledge.
Low-cost solutions were encouraged and implemented through innovations developed within the local communities.[16–21]	Cost barriers can be overcome by a frugal engineering approach involving off-the-shelf components using minimal resources.
Industries that rely on manufacturing processes and systems were severely impacted (e.g., meat-manufacturing plants).[22]	Manufacturing close to the point-of-need is necessary.

multiple sectors.[1] At the same time, several "physical" technologies/operations were critically impacted with the manufacturing sector reporting negative impacts.[2] Industries around the world reacted to the challenges by addressing them at local and global scales. According to Eurostat,[3] globally, gross domestic product growth rates had a negative impact (~1–3 %) immediately after the COVID-19 pandemic. **Table 1** presents representative observations along with the key lessons at the component, part, and systems levels. The technical challenges presented through these examples illustrate the need for the development of future manufacturing systems realized by incorporating the lessons learned. This is critical from the point of view of understanding the fundamental science and developing engineering foundations for enabling an infrastructure that is better equipped to tackle any future catastrophic events[4] as opposed to reacting to such events. This paper presents a case for the development of a resilient approach, specifically in the context of manufacturing by incorporating a hybrid manufacturing method allowing for material and process flexibility.

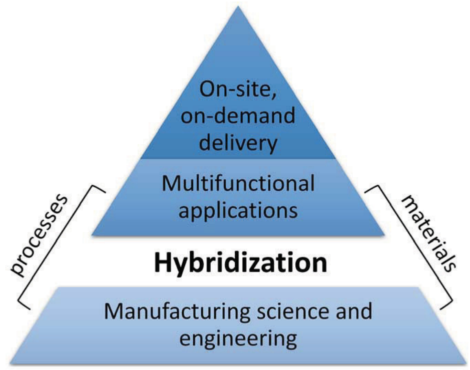
REQUIREMENTS FOR A RESILIENT MANUFACTURING INFRASTRUCTURE

Resilience is defined as "the intrinsic property of a system to resist, and/or recover from, and/or adapt to a new and improved state in a time much smaller than the overall lifetime of the system, under known unknown or unknown stochastic or random perturbation(s)."[5] As discussed previously, the COVID-19 pandemic, because of the requirement of rapid response, challenged the resiliency of traditional sequential manufacturing operations. Especially, the stress put by the COVID-19 pandemic called for key requirements identified in **Table 1**, including but not limited to the following: one, quick response time; two, cost reduction; three, the ability to address multiple operational functions in one place; four, the use of fewer resources for sustainability; and five, agile manufacturing. These requirements can be enabled through manufacturing systems by incorporating the following performance attributes: one, design for performance enabled by advanced manufacturing; two, near-net-shape manufacturing of complex components in one piece; three, at-scale innovation (rapid progression of innovations from ideation to production); and four, point-of-need, on-demand, and on-site manufacturing.

To meet the outlined demands, advanced functional materials with required properties and their combinations are needed at the component, assembly, and system levels, enabled through the resilient manufacturing platform. Traditional manufacturing processes (additive and subtractive) are discretized in terms of their applicability and material-specific process optimization and thus provide limited adaptability in terms of materials, design configurations, or combinations thereof. Additionally, assembly, finishing, and packaging will require separate sequential processing steps, increasing the overall cost and turnaround time. Thus, an approach based on hybridization of additive, subtractive, and transformative manufacturing methods in one manufacturing platform will be better suited for the demands of multifunctional and multi-material integrative products and is the focus of this paper. The hybrid approach (through hybridization of multiple materials and processes) discussed in this paper is depicted in **figure 1**. As depicted in **figure 1**, the hybridization of materials and processes is a technical knowledge gap going from fundamental science toward the realization of multi-material and multifunctional parts with application-

FIG. 1

Hybridization of materials and processes for resilient manufacturing.



specific designs. In addition to material and process flexibility, the hybridization approach enables resilient manufacturing through the attributes of reduction in energy/space footprint, near-net-shape manufacturing capability, and modularity, especially as these demands are acute during a pandemic and similar catastrophic events as discussed in the following sections. The upcoming section titled "Hybrid Manufacturing Approach: Overview" provides a background and overview of hybrid manufacturing, especially in the context of hybrid additive manufacturing (Hybrid-AM) approaches and benefits. The "Case Studies for Resilient Hybrid Manufacturing" section discusses the representative Hybrid-AM case studies to illustrate the previously discussed merits. The paper concludes by providing a future perspective toward convergent manufacturing.

Hybrid Manufacturing Approach: Overview

Hybrid manufacturing processes are defined as the following: "Manufacturing processes based on the simultaneous and controlled interaction of process mechanisms and/or energy sources/tools having a significant effect on the process performance."[6] This definition applies to the use of simultaneous energy sources to increase the machining efficiency of the primary process. This paper especially focuses on the hybrid approach using additive manufacturing (AM) for design and process flexibility combined with other subtractive processes through representative examples. This section provides an overview of existing Hybrid-AM equipment along with the benefits of the Hybrid-AM approach addressing the previously discussed needs. The authors also note that the hybridization of materials along with processes is also crucial for the resilient manufacturing platform and is discussed as a future perspective in the section titled "Future Manufacturing: From Hybridization to Convergence."

HYBRID-AM: STATE-OF-THE-ART

AM processes are being applied increasingly within aerospace, biomedical, automotive, and strategic fields because of their ability to process complex part geometries and lightweight structures. Yet, several challenges (microstructure integrity, larger process times, and limited build volumes) remain for widespread applications.[7,8] In the context of AM, hybrid processing can be thought of as a combination of an additive process with either a subtractive or a transformative processing step. Hybrid-AM has been defined as "the use of AM with one or more secondary processes or energy sources that are fully coupled and synergistically affect part quality, functionality, and/or process performance."[8] **Table 2** provides a summary of existing commercial Hybrid-AM machines. At this stage, these machines are primarily focused on metallic materials, where a specific metal AM technology (such as directed energy deposition or laser powder bed fusion) can be combined with the traditional Computer Numerical Control machining operations. The advantage of such integration is that the same system houses the additive and subtractive components and therefore, appropriate tool paths can be programmed for continuous sequential operation without taking the part out and retooling, saving time and cost, which is especially key during urgencies like pandemics. The table also highlights the modular nature of the existing hybrid manufacturing equipment.

TABLE 2
List of Hybrid-AM systems and their features

Equipment	Types of Processes	Modularity	Other Features	Manufacturer, Location
Lumex Avance-60	Laser powder bed fusion, milling, and finishing	All tools are within the same machine automated setup	Loose powder is collected and reused	Matsuura Machinery Corporation, Fukui-city, Japan
Integrex i-400AM	Laser-based metal AM (DED) and CNC milling and turning	Laser cladding modular heads	Joining of different metals for part repair	Yamazaki Mazak Corporation, Ōguchi, Japan
Ambit™	Laser-based metal AM, laser cutting and finishing, and CNC milling and turning	Turnkey nozzles/ machining heads	Also has a surface inspection tool for in situ monitoring	Hybrid Manufacturing Technologies, McKinney, TX
LENS 860	Laser cladding (DED), CNC machining	All tools are within the same machine automated setup	Optional 4- and 5-axis motion system	Optomec Inc., Albuquerque, NM
LaserTec 65 DED Hybrid	Laser cladding (DED), CNC machining	All tools are within the same machine automated setup	Real-time process monitoring for laser-power regulation	DMG Mori, Tokyo, Japan
3D Hybrid Metal 3D Printing Tools	Electric arc, laser metal deposition, and cold spray	Hybrid modules integrate with existing CNC machinery		3D Hybrid Solutions, Los Angeles, CA
OPM250 Metal 3D Printer	Laser-metal sintering and high-speed milling	16-position automatic tool changer	Material recovery system	Sodick, Schaumburg, IL
Millturn 80	Laser cladding with milling/turning machine	Modular laser-cladding unit for operation	Nonlinear tool paths also possible	WFL Millturn Technologies GmbH & Co. KG, Linz, Austria
MPA-40	Thermal spray deposition and milling	Thermal spray unit integrated within 5-axis machining setup	Uses sacrificial support material to temporarily fill cavities during spraying	Hermle AG, Gosheim, Germany
CybaCAST Hybrid	Laser powder deposition and milling	6-axis setup holds the powder deposition and milling tools	Ability to mix different metal powders for alloying	Cybaman Technologies, Cheshire, UK
SonicLayer® 4000	Ultrasonic Additive Manufacturing (UAM) with CNC machining	Ultrasonic welding head incorporated into 3-axis mill	Used metal foils as input for welding head	Fabrisonic LLC, Columbus, OH

Note: Table 2 represents commercially available metal Hybrid-AM machines/equipment as of this year to the best of the author's knowledge. The list presents representative models from the equipment manufacturer and does not include similar models from the same manufacturer. More information on hybrid systems can be found in the list of additive manufacturing process compiled by the SME.[23]

BENEFITS OF HYBRID-AM

Hybrid-AM combines the benefits of AM with an enabling secondary operation to achieve a better part. For example, laser-based surface processing (e.g., shock peening) can be combined to manage the residual stress profiles in parts based on the target application and required properties. AM offers the freedom to manufacture complex designs, thus reducing multiple assembly steps and production time. Furthermore, because part designs are digitized, they can be easily reconfigured/customized based on the specific application need, thus increasing the flexibility in manufacturing. When combined with the appropriate subtractive/transformative process, hybridization allows for complex parts with the desired surface finish and mechanical properties to be manufactured in one Hybrid-AM platform. Additionally, the digitization in AM processes allows the operations to be automated, enabling "lights-out manufacturing," meaning that continuous human control is reduced and remote work is possible, especially when social distancing during a pandemic restricts human participation. The case studies to be presented emphasize the advantages of hybridizing AM with milling. While AM enables conformal cooling channels and a high degree of automation to manufacture complex geometries, Hybrid-AM permitted finished machined surfaces on internal features, automation of milling that would normally be very labor-intensive, and cutting of complex or high-aspect ratio features that would normally require separate tooling. The hybridizing methodology reduces lead times to produce parts by eliminating manufacturing steps, such as electric discharge machining, discussed in the second case study. As a result, substantial cost savings are possible in terms of labor, materials, and processing that are unachievable with AM alone.

This paper discusses the outlined benefits through the illustrative examples using a Matsuura Lumex Avance-25 Hybrid-AM system. The equipment utilizes laser powder bed fusion of metal powders as the AM process in combination with high-speed, high-precision milling. The setup also incorporates pre-milling powder suction to allow for faster cutting-feed rates. The powder handling (supply, collection, and reuse) can be fully automated, thus reducing the need for continuous human monitoring (crucial in the post-pandemic remote working conditions). The following section presents case studies discussing the hybridization of multiple processes to allow repurposing, adaptation, and rapid processing.

Case Studies for Resilient Hybrid Manufacturing

The following sections highlight the advantages of Hybrid-AM through two case studies to demonstrate resiliency. Here, resiliency refers to a system's ability to adapt to an urgent and evolving need, e.g., during the pandemic. The first case study presents Hybrid-AM of an injection molding tool for ventilator filter housing. The second case study presents Hybrid-AM of an injection molding tool for a hand-tool device.

CASE-1: EFFICIENT TURNAROUND OF A VENTILATOR FILTER HOUSING

One example benefiting from hybrid manufacturing was a ventilator filter housing (Table 3 and fig. 2). Ventilator filters protect patients on mechanical ventilation from inhaling harmful pathogens while also limiting the outbound spread of infection from exhaled gas. These filters play a critical role in the healthcare frontlines by helping prevent cross contamination to caregivers and other patients. The plastic housings have a complex geometry comprised of internal and external features needed for the ventilation circuit and for the condensate drainage system. Precision net-shape surfaces from injection molding of the housings are needed to maintain viral and bacterial filtration efficiency greater than 99.999 %. Thus, manufacturing directly plays a critical role in ensuring health and safety along with high-functional quality.

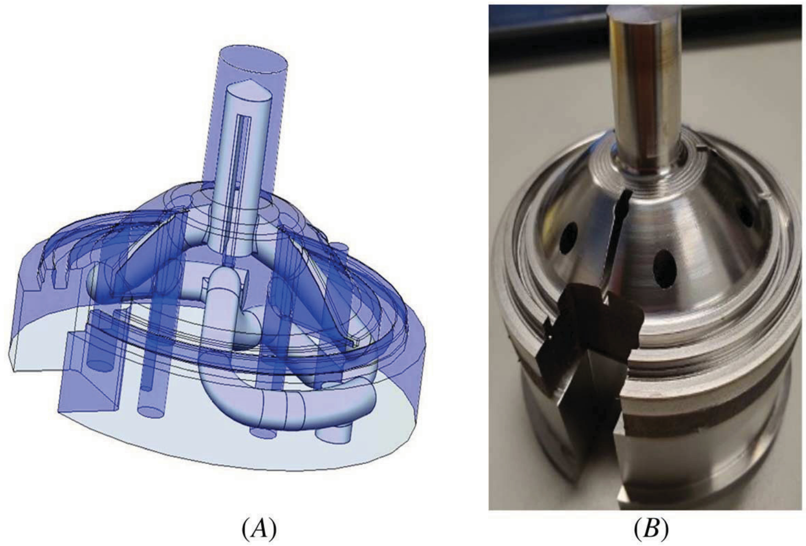
The housings are traditionally manufactured by first machining the negative form within a solid steel billet to create a mold. Next, the mold components are assembled into a tool and heated plastic is injected into the mold cavity via an injection molding machine. Once cooled, the plastic housing is ejected from the mold cavity, and the injection cycle repeats. The lead times to produce new tooling is the largest rate-limiting barrier during the

TABLE 3
Key attributes of ventilator filter housing

Attributes	
Product/part:	Injection molding tool
Application:	Ventilator filter housing
Materials:	Maraging steel mold for injecting plastic housing
Product/part Size:	100 mm × 100 mm × 125 mm
Types of processes hybridized:	Powder bed fusion and milling
Additive:	320 W; 700 mm/s; 0.12-mm hatch; 50-μm layer thickness
Milling:	0.6–2.0-mm ball nose, end mills at 45,000 RPM, and 600–2,000-mm/min feed rate
Key merits offered by hybrid processing technique:	• Reduced lead time • Reduced cycle time • Improved efficiency

FIG. 2

Ventilator filter housing conformally cooled core manufactured using a maraging steel tool printed and milled on a Matsuura Lumex Avance-25: (*A*) model revealing conformal cooling channels and (*B*) final printed and milled core. (Images reproduced with permission of Matsuura USA.)



pandemic to rapid and resilient manufacturing in the tool and die industry. Furthermore, the cooling cycle, which is the time required for the part to solidify and eject from the mold cavity, is the most time-consuming activity that inhibits production capacity. The greatest opportunity to impact production capacity is shortening cooling cycles with more efficient thermal management. However, traditional manufacturing limits innovative designs. Hybridizing freedom of design with AM and the ability to machine during printing enables complicated parts and reduced time to manufacture, allowing the fastest response time.

This case employed Hybrid-AM using a Matsuura Lumex Avance-25 to rapidly print an injection molding tool for a ventilator filter housing. The Lumex combines powder bed fusion with milling to enable porous, hollow, net shape, and integrated structures unachievable by traditional machining. A noteworthy advantage of AM is the ability to print porous mold sections that allow molding gases to vent directly through the section of the mold that was printed porous, thus reducing back pressure within the mold cavity and allowing the part to be produced with a higher injection speed to eliminate part defects caused by superheated unvented gas within the cavity. As a result of hybridizing printing and milling, the lead time to produce the housing in production quantities was reduced by six months. Furthermore, the tool's design increased efficiency in producing ventilator filter housings by reducing cycle times more than 30 %.

CASE-2: LIGHTS-OUT MANUFACTURING OF AN INJECTION MOLDING TOOL

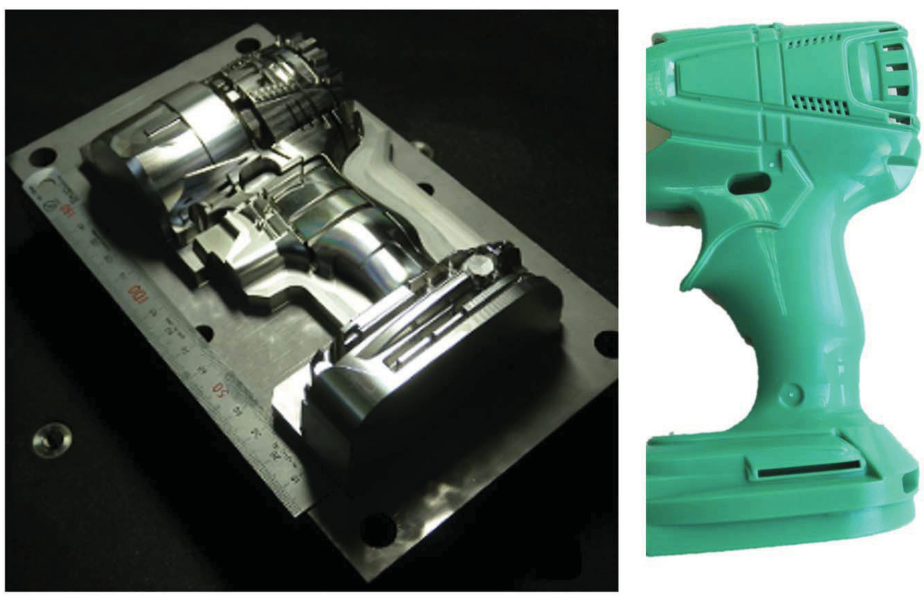
This case study highlights the additional manufacturing advantages of using a Matsuura Lumex Avance-25 to produce a three-piece injection molding tool (Table 4 and fig. 3) that traditionally consists of 25 separate components. For example, the ability to achieve precision machined surfaces on complex internal and external geometric features (e.g., long narrow ribs, deep slots, and internal cavities) reduces the production time from weeks to days by eliminating the need for electric-discharge machining of mold components/features as well as the time required to manufacture the corresponding electrodes (fig. 4). The reduction of parts also reduces the need for complicated and time-consuming assemblies.

A key advantage of Hybrid-AM to highlight is the ability to quickly adapt a design for customization (e.g., custom-made device), or perhaps more important is the ability to modify a design without long lead times necessary for customized retooling. Hybrid-AM naturally enables flexibility and reconfigurability that would be too slow or cost-prohibitive with traditional manufacturing. Lessons learned from the COVID-19 pandemic emphasized the need for a "catastrophe manufacturing" paradigm that allows a company to pivot from

TABLE 4
Key attributes of an injection molding tool

Attributes	
Product/part:	Injection molding tool
Application:	Hand-tool device
Materials:	Maraging steel mold for injecting plastic housing
Product/part Size:	160 mm × 100 mm × 50 mm
Types of processes hybridized:	Powder bed fusion and milling
Additive:	320 W; 700 mm/s; 0.12-mm hatch; 50-μm layer thickness
Milling:	0.6–2.0-mm ball nose end, mills at 45,000 RPM, and 600–2,000-mm/min feed rate
Key merits offered by hybrid processing technique:	• Lights-out manufacturing • Increased productivity • Increased efficiency • Reduced complexity • Reduced part count • Reduced lead time • Reduced cycle time • Lowered cost

FIG. 3 (*A*) Injection molding tool printed and milled on a Lumex Avance-25 and (*B*) resulting plastic part after injection molding. (Images reproduced with permission of Matsuura USA.)



(*A*) (*B*)

manufacturing aerospace components, for example, to personal-protective equipment with practically no lead times. This calls for manufacturers to adopt a vending-machine platform concept first introduced by Meisel and Williams[9] that enables flexibility and short manufacturing lead times.

In a hybrid process that combines printing and milling, the time to manufacture a mold is mainly dependent on build height and machining complexity. The machining time is a function of the total volume to be machined, the number of cutting steps with tool changes (e.g., roughing cutters and finishing cutters), and the frequency at which machining is needed (e.g., the default is every 10 layers). Depending on the build complexity, machining time can constitute more than half of the total production time. However, the advantage of a hybrid method is the

FIG. 4 Simplified hybrid manufacturing of (*A*) a single-part mold that eliminates the need for (*B*) electrodes used to produce (*C*) multiple mold components. (Images reproduced with permission of Matsuura USA.)

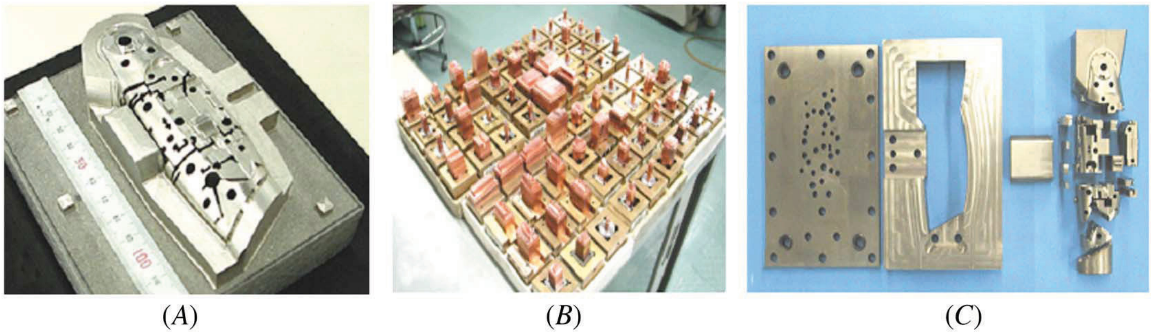


FIG. 5 Advantages of producing an injection molding tool using hybrid manufacturing compared to conventional manufacturing. (Image reproduced with permission of Matsuura USA.)

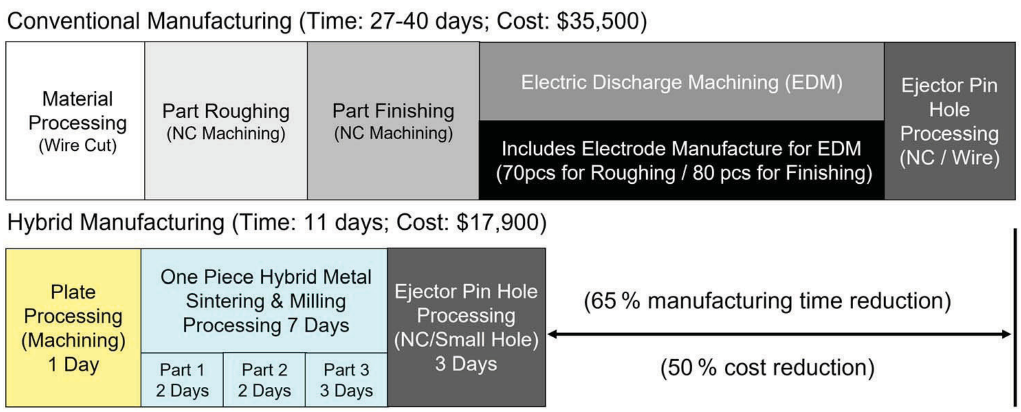
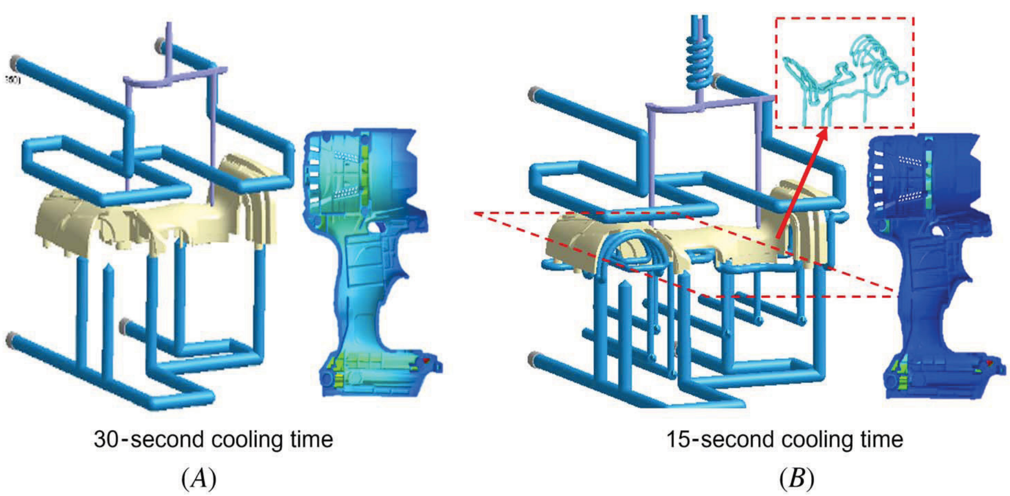


FIG. 6 Reduction of hotspots and cooling time for an injection molding tool: (*A*) conventional manufacturing of nonconforming cooling channels and (*B*) hybrid manufacturing of complex conforming cooling channels. (Modified image reproduced with permission of Matsuura USA.)



ability to continuously print and machine beyond traditional working hours, which enables truly lights-out manufacturing that requires little or no intervention during production. As a result, the time for production was reduced from 27–40 days to 11 days, and the cost was reduced by nearly 50 % (fig. 5), based on the invoices received from the supplier of the component and based on an a 100 USD/h average shop rate.

Another advantage of Hybrid-AM for injection molding is the ability to manufacture conformal cooling channels that reduce cycle time (fig. 6). Conformal cooling channels enable more efficient heat sinks that reduce hot spots. Excessive hot spots result in mold burn and higher defect rates. Using milling during AM enabled more complex channels that reduced cooling time from 30 s to 15 s. This increases production efficiency by enabling more parts per hour to better combat supply challenges.

Future Manufacturing: From Hybridization to Convergence

Convergence is defined as "the merging of distinct technologies, industries, or devices into a unified whole."[10] Convergence is a natural process also in biology or social science whereby it is an action on converging to obtain uniformity or union. The authors foresee hybridization of the processes just discussed as an onset of a trend whereby future manufacturing will converge heterogeneous materials, processes, and tools at higher levels along with physical-digital systems (Industry 4.0) in a unified platform to obtain far higher levels of functionality, effectiveness, reconfigurability, adaptability, and efficiency for the overall manufacturing enterprise.

Convergent manufacturing can be defined as an approach that converges heterogeneous materials, processes (additive, subtractive, and transformative), and related tools as inputs yielding functional devices and components for systems as an output while equipped with Industry 4.0 principles of connectivity, data-driven optimization, modularity, flexibility, reconfigurability, and portability.

Convergent manufacturing aims to reduce inertia and latency because of the number of heterogeneous variables that are at the disposal of the manufacturer while simultaneously offering modularity and selectivity

FIG. 7

Convergent manufacturing through hybridization.

to address varying end goals, especially when addressing emergencies such as a global pandemic. During such emergencies, limitations of existing infrastructure experienced by manufacturers and supply chains are singular-material options (e.g., separate polymer or metal three-dimensional printers), physical inertia and footprint of tools, heterogeneous digital interfaces adding latency, and limited connectivity from design to delivery. Portability could significantly add value to allow rapid delivery at point-of-service and rapid response for one-of-a-kind manufacturing to address diverse needs. Convergence, through the way of a hybridization approach, could allow manufacturing of design for addressing urgency rather than design for manufacturing, which limits solution providers like frontline medical workers' ability to serve. The authors propose the following model (**fig. 7**) for convergence in manufacturing achieved through hybridization, as a summary of the outlined discussion.

The World Economic Forum anticipates more frequent pandemics and higher vulnerability to human civilization.[11] This is collectively driven by a growing human population, diversity of human habitual behaviors, hyperphysical and digital mobility across the world, and a growing life expectancy. The readiness of the manufacturing enterprise becomes mission-critical, and convergence will be an essential part of that global manufacturing community to deliver on demand at a given point and time. It is foreseen that convergence will be necessary and boosted because of the lessons learned from the COVID-19 pandemic, enabling future readiness.

The previously discussed trends and developments for convergence in manufacturing need attention to address the following barriers where investment in research, development, and commercialization is timely. The first barrier is a lack of understanding of fundamental science in convergent manufacturing. For example, it is critical to understand how interfaces among processes and materials achieve multifunctional heterogeneous integration. The second barrier is in the area of engineering. For example, designing and engineering reconfigurable hardware and software and their seamlessly connected interfaces are critical in reducing capital cost and at the same time allowing portability. The third barrier is scale-up and commercialization. For example, convergent systems potentially need major initial investments analogous to the scale-up and commercialization of COVID-19 vaccines. Harmonic win-win, public-private partnerships for the public good are essential for enabling scale-up and commercialization. This also has a potentially significant impact on job creation in manufacturing. This will complement job creation in the service sector and translate research and development by taxpayer funding into a public good, allowing the opportunity for equity. Lastly, the creation of a workforce will take a multipronged approach as it will be able to attract and train Gen Z and future generations and also leverage the experience of the currently aging workforce while establishing means of continuous learning for human-source readiness.

Conclusions

This paper discusses the requirements of resilient manufacturing systems based on the lessons learned during the COVID-19 pandemic. Manufacturing innovations enabled by the hybridization of processes present opportunities to provide solutions with functionality, speed, and cost-efficiency necessary during an emergency. This paper discussed a comparative analysis of available Hybrid-AM platforms and the application of one of them for two anecdotal applications including offering solutions for frontline workers in the pandemic. The paper also discusses intricacies from these applications in terms of design, process parameters, and functional behavior in Hybrid-AM. Lastly, this paper envisions the effective onset of the trend in hybridization, leading to future manufacturing, convergent manufacturing (**fig. 7**) for convergence of heterogeneous materials, processes, and tools, as well as physical-digital systems to address rapidly approaching demands for delivery parts, products, and services at points of interest during the next local emergency, global emergency, or both.

ACKNOWLEDGMENTS

The author (MPS) acknowledges partial support from NSF CMMI Grant No. 1846478.

References

1. S. Whitelaw, M. A. Mamas, E. Topol, and H. G. C. Van Spall, "Applications of Digital Technology in COVID-19 Pandemic Planning and Response," *Lanclet Digital Health* 2, no. 8 (June 2020): E435–E440, https://doi.org/10.1016/S2589-7500(20)30142-4
2. D. Wee, "COVID-19 Reshapes Manufacturing Landscape, New Google Cloud Findings Show," *Inside Google Cloud*, December 10, https://web.archive.org/web/20211109201653/https://cloud.google.com/blog/topics/inside-google-cloud/covid-19-reshapes-manufacturing-landscape
3. Eurostat Statistics Explained, "GDP Growth Rates Published for 2020Q1 % Change to the Previous Quarter, Based on Seasonally Adjusted Data," Eurostat Statistics Explained, 2020, http://web.archive.org/web/20210830135028/https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File%3AGDP_growth_rates_published_for_2020Q1_%25_change_to_the_previous_quarter%2C_based_on_seasonally_adjusted_data_.png
4. E. Yong, "Where Year Two of the Pandemic Will Take Us," *The Atlantic*, December 29, 2020, http://web.archive.org/web/20210317032937/https://www.theatlantic.com/health/archive/2020/12/pandemic-year-two/617528/
5. A. Malshe, S. Bapat, K. Rajurkar, and S. Melkote, "Biological Strategies from Natural Structures for Resilience in Manufacturing," *CIRP Journal of Manufacturing Science and Technology* 34 (August 2021): 146–156, https://doi.org/10.1016/j.cirpj.2020.10.010
6. B. Lauwers, F. Klocke, A. Klink, A. E. Tekkaya, R. Neugebauer, and D. Mcintosh, "Hybrid Processes in Manufacturing," *CIRP Annals* 63, no. 2 (January 2014): 561–583, https://doi.org/10.1016/j.cirp.2014.05.003
7. P. Stavropoulos, P. Foteinopoulos, A. Papacharalampopoulos, and H. Bikas, "Addressing the Challenges for the Industrial Application of Additive Manufacturing: Towards a Hybrid Solution," *International Journal of Lightweight Materials and Manufacture* 1, no. 3 (September 2018): 157–168, https://doi.org/10.1016/j.ijlmm.2018.07.002
8. M. P. Sealy, G. Madireddy, R. E. Williams, P. Rao, and M. Toursangsaraki, "Hybrid Processes in Additive Manufacturing," *Journal of Manufacturing Science and Engineering, Transactions of the ASME* 140, no. 6 (June 2018): 060801, https://doi.org/10.1115/1.4038644
9. N. A. Meisel and C. B. Williams, "Design and Assessment of a 3D Printing Vending Machine," *Rapid Prototyping Journal* 21, no. 5 (August 2015): 471–481, https://doi.org/10.1108/RPJ-07-2014-0081
10. *Merriam-Webster*, s.v. "convergence (n.)," https://www.merriam-webster.com/dictionary/convergence
11. K. Whiting, "Coronavirus Isn't an Outlier, It's Part of Our Interconnected Viral Age," World Economic Forum, March 4, 2020, http://web.archive.org/web/20210317040721/https://www.weforum.org/agenda/2020/03/coronavirus-global-epidemics-health-pandemic-covid-19/
12. A. Malshe and S. Bapat, "Quo Vadimus: Humanism, Going Beyond the Boundaries of Capitalism and Socialism," *Smart and Sustainable Manufacturing Systems* 4, no. 3 (October 2020): 338–340, https://doi.org/10.1520/SSMS20200060
13. A. Shokrani, E. G. Loukaides, E. Elias, and A. J. G. Lunt, "Exploration of Alternative Supply Chains and Distributed Manufacturing in Response to COVID-19; a Case Study of Medical Face Shields," *Materials & Design* 192 (July 2020): 108749, https://doi.org/10.1016/j.matdes.2020.108749
14. O. Okorie, R. Subramoniam, F. Charnley, J. Patsavellas, D. Widdifield, and K. Salonitis, "Manufacturing in the Time of COVID-19: An Assessment of Barriers and Enablers," *IEEE Engineering Management Review* 48, no. 3 (September 2020): 167–175, https://doi.org/10.1109/EMR.2020.3012112
15. Supply Chain Dive Staff, "Tracking US Manufacturers' Shift to PPE during the Coronavirus Pandemic," Supply Chain Dive, August 24, 2020, https://web.archive.org/web/20210515021141/https://www.supplychaindive.com/news/us-manufacturers-ppe-coronavirus-pandemic/576665/
16. M. Harris, Y. Bhatti, J. Buckley, and D. Sharma, "Fast and Frugal Innovations in Response to the COVID-19 Pandemic," *Nature Medicine* 26, no. 6 (May 2020): 814–817, https://doi.org/10.1038/s41591-020-0889-1
17. T. E. Narasimhan, "Portable Hospital to Vaccines: Low-Cost Covid Solutions from Universities," *Business Standard*, July 18, 2020, http://web.archive.org/web/20210317034536/https://www.business-standard.com/article/current-affairs/portable-hospital-to-vaccines-low-cost-covid-solutions-from-universities-120071701139_1.html
18. D. G. Schroeder, "Turn Your Covid-19 Solution into a Viable Business," *Harvard Business Review*, July 2, 2020, http://web.archive.org/web/20210317034738/https://hbr.org/2020/07/turn-your-covid-19-solution-into-a-viable-business
19. J. M. Pearce, "A Review of Open Source Ventilators for COVID-19 and Future Pandemics," *F1000Research* 9 (2020): 218, https://doi.org/10.12688/f1000research.22942.2
20. L. Fiorineschi, F. S. Frillici, and F. Rotini, "Challenging COVID-19 with Creativity: Supporting Design Space Exploration for Emergency Ventilators," *Applied Science* 10, no. 14 (July 2020): 4955, https://doi.org/10.3390/app10144955
21. A. P. Malshe, D. Agonafer, S. Bapat, and J. Cao, "A Case for Frugal Engineering and Related Manufacturing for Social Equity," *The Bridge, National Acedemy of Engineering (NAE)* 51, no. 1 (2021): 54–62.
22. A. Weersink, M. von Massow, N. Bannon, J. Ifft, J. Maples, K. McEwan, M. G. S. McKendree, et al., "COVID-19 and the Agri-food System in the United States and Canada," *Agricultural Systems* 188 (March 2021): 103039, https://doi.org/10.1016/j.agsy.2020.103039
23. SME, "Additive Manufacturing Processes," SME, 2018, http://web.archive.org/web/20211122040417/https://www.sme.org/globalassets/sme.org/technologies/medical-manufacturing/amtechnologies.pdf